A MULTIZONE TECHNIQUE FOR BILLET INSPECTION

Edward J. Nieters, Robert S. Gilmore,
Robert C. Trzaskos, and John D. Young
GE Corporate Research and Development Center
P.O. Box 8
Schenectady, NY 12301

David C. Copley, Patrick J. Howard,
Michael E. Keller, and William J. Leach
GE Aircraft Engines
Quality Technology Center
One Neumann Way M/D Q45
Cincinnati, OH 45215

INTRODUCTION

An ultrasonic inspection system has been developed in response to FAA recommendations for improved inspection of titanium billet [1]. This prototype system – called Multizone – has been transitioned to the factory floor and has inspected 1,000,000+ pounds of Ti billet in 1993–94. It is a real–time, PC based platform that employs custom built analog electronics using up to 8 parallel (non–multiplexed) channels, each with a remote pulser/receiver matched to the ultrasonic transducer. Scanned helically, the billet is divided into concentric zones with a focused transducer used to acquire peak detected C–Scan image data for each zone. The depth of each zone is established by the depth of focus of that transducer. C–Scan image data from all channels are displayed simultaneously on a 1024x1280 CRT and scroll as the inspection advances along the billet length. The data are written to optical storage upon completion of the inspection. The analog electronics are fully synchronous and could provide a baseline system for the acquisition of full waveforms. Custom post scan analysis software has been developed to detect flaws using signal to noise based algorithms. This software provides more reproducible results than conventional systems and greatly reduces operator fatigue and the chance for error. This paper will discuss the system architecture and operation. A companion paper in this volume discusses inspection results. [2]

SYSTEM RATIONALE

A goal in aircraft engine manufacture is to inspect rotating components to the highest practicable sensitivity. Prior to the Multizone system, the conventional test methods were limited in sensitivity due to material noise and poor focusing. In addition, there was no digital data acquisition or storage. To correct this situation, a system was designed that would use focused transducers to overcome material noise and therefore improve detection. However, multiple compound focused transducers were required to inspect the billet volume to uniform sensitivity. A computer system was developed to provide digital data acquisition. The capability to permanently store the data was envisioned so a write–once read–many (WORM) optical disk was added.

The system architecture is basically comprised of four parts: 1) the billet material to inspect, 2) the transducers, 3) the analog electronics, and 4) the computer system. Since most titanium suppliers already have ultrasonic scanners for billets, the Multizone components are designed so that these existing scanners can be retrofitted for Multizone inspection.

BILLET MATERIAL

Aircraft engine grade titanium billets encompass several alloys: Ti–6Al–4V (Ti64), Ti–5Al–2Sn–2Zr–4Mo–4Cr (Ti17), and Ti–6Al–2Sn–4Zr–2Mo (Ti6–2–4–2). The titanium refining process produces large cylindrical ingots. Acoustic noise resulting from large grain size, high porosity, and shrink cavities makes ultrasonic inspection impossible at this point. Ingots are forged down into billets with diameters of 6" to 13" and cropped into segments of length 60" to 200". The billet surface is then machined to remove any surface oxides, nitrides, scale, etc. At this stage the grain size is smaller and the forging process has removed most of the ingot porosity making ultrasonic inspection feasible. Material that passes the billet inspection is cut into smaller lengths called "mults" which are forged for aircraft engine rotating parts. Wrought titanium costs roughly increase by an order of magnitude for each step as the material moves from billet to raw forging to finished machined part. Defects found at the billet stage result in scrapped material with the lowest added value. Clearly this is the most desirable time for inspections from an economic standpoint.

TRANSDUCERS

Before Multizone, a typical industrial billet inspection used a single transducers which was line focused. Because a transducer can not be focused beyond its near field limit and the nearfields of these transducers are at most 2.0" in titanium, the transducers can not produce the line focus intended for the billet center. As a result, much of the material is not inspected with focused sound since it falls outside the transducer near field (Figure 1). Flaws located near billet centerline are particularly difficult to find with this technique. While Distance–Amplitude Correction (DAC) is employed to produce uniform target response at different depths, this greatly increases the noise at the billet center.

Multizone uses 4 to 8 transducers of 5 MHz frequency each point focused at a different depth in the material. Each transducer covers a zone with size determined by the transducer depth of field and each transducer increments along the billet at a distance of half the beam diameter. Equations 1 and 2 describe the focal zone for a transducer of diameter d and focal length F. [3]

$$\varepsilon_z = 3.6\lambda\left[\frac{F}{d}\right]^2\frac{c_1}{c_2} \qquad (1)$$

$$\varepsilon_x = 1.03\lambda\left[\frac{F}{d}\right] \qquad (2)$$

Equation 1 gives the –3 dB depth of field ε_z where c_1 is the sound velocity in water (0.058 in/usec), c_2 is the sound velocity in titanium (0.243 in/usec), and λ is the wavelength (0.049 in. in titanium at 5 MHz). Equation 2 gives the –6 dB beam diameter ε_x for the same parameters. A typical multizone transducer produces 5 MHz, F/8.0 beams that are approximately 0.1" diameter and 0.8" depth of field in titanium. At deeper depths, larger F numbers are used due to the limitation in element diameters produced by commercial vendors. By increasing the transducer size and depth in the material of its focal zone, overlapping foci are produced to uniformly inspect the billet volume (Figure 1). The transducers are fitted with dual curvature lenses to produce a diffraction limited

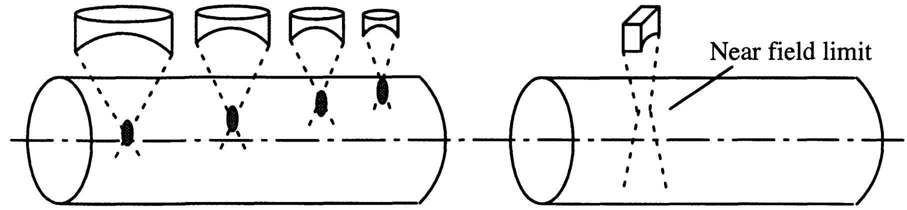

Figure 1. Multizone inspection vs. Typical Industrial inspection

symmetrical focus. This configuration provides more uniform sensitivity vs. depth for a given scan rate. DAC is not used with Multizone because all material is inspected in the –3 dB depth of field.

The advantages of using focused sound can be seen experimentally. Figure 2 shows three separate experiments where a transducer focused sound in a flat bottom hole (FBH) block (a) on the surface, (b) half way through the material, and (c) in the plane of the holes. The C–scan data from these inspections show that the signal to noise is much greater when the transducer is focused in the plane of the flaw. Note that signal amplitude is approximately the same in all tests but by detecting with the focal zone in the plane of the flaw, less of the surrounding material is insonified which produces much less acoustic noise.

ELECTRONICS

The ultrasonic instrument uses custom analog electronics with up to 8 parallel, non–multiplexed channels based on the NIM architecture. Each channel has an analog bandwidth of 50 kHz to 25 MHz. The parallel, non–multiplexed architecture was used to eliminate any unattenuated sound which might interfere with a given channel's signal. A multiplexed solution also introduces possible speed limitations. The transducers differ in size by a factor of 4 which corresponds to a difference in capacitance of a factor of 16 so each transducer has its own remote pulser/receiver which is matched to that specific transducer. The user can set various parameters for each channel such as attenuation, signal gate delay and width, and triggering rate. The data generated for each channel/zone is an analog, peak–to–peak C–scan voltage ranging from 0 to 10 volts which is sent to the computer for display and storage. The gated peak detectors have a 40 dB linear dynamic range.

COMPUTER

The computer is a 486–based PC operating at 66 MHz with 64 MB of RAM running MSDOS and Windows. The large amount of RAM permits storage of data from all 8 channels in memory as it is acquired. This eliminates time–consuming disk accesses during acquisition. Standard data acquisition boards are used for digital handshaking signals between the computer and the electronics and for digitization of the analog C–scan data A 21" 1280x1024 resolution color monitor allows all 8 channels to be displayed simultaneously during acquisition. The archival storage requirement was achieved using a write–once–read–many (WORM) optical disk for archiving the image data. Report generation is accomplished using a high quality color Postscript printer.

The display is critical to system operation. Figure 3 gives a schematic describing how a single channel would be displayed for a billet. With the high resolution screen, we have room to display all 8 channels simultaneously in this fashion. Dividing the screen into eight 128–pixel high horizontal strips, all the data are displayed on the screen as the scan progresses. The horizontal drawing length is 1024 pixels wide which corresponds to 1024 billet revolutions. When the display reaches the right margin, the entire drawing screen

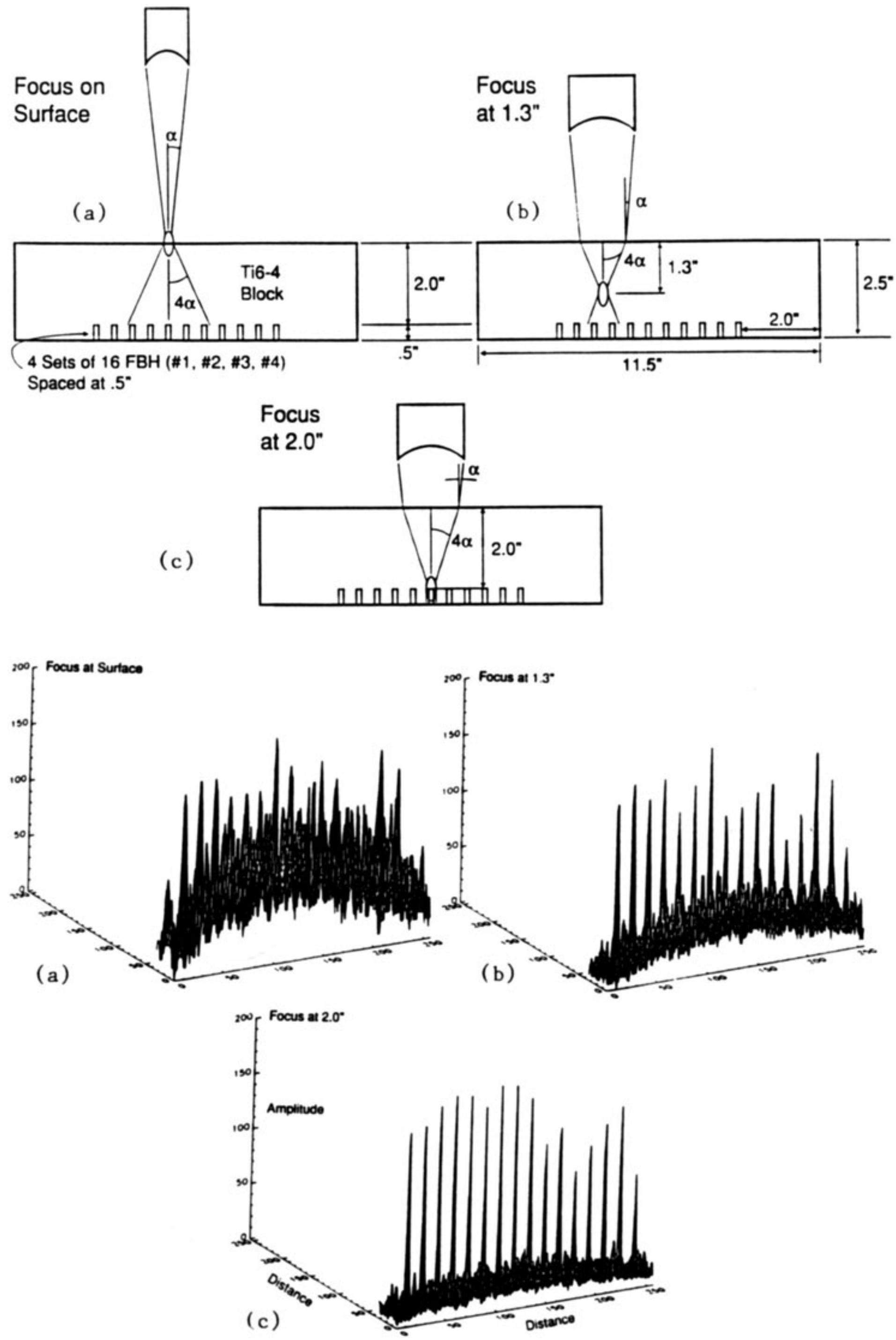

Figure 2. Experimental results using focused sound at various depths in flat–bottom hole block

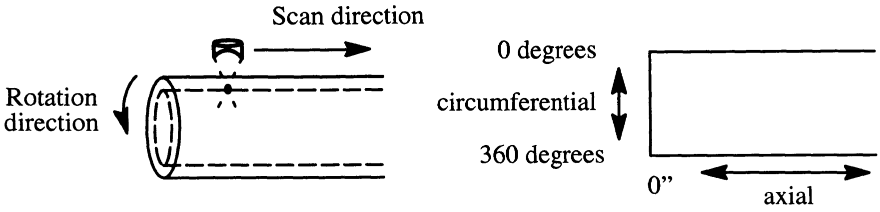

Figure 3. Single channel billet C–scan display

scrolls one pixel to the left making the screen scroll right to left during scanning. A variety of color palettes including grayscale are available and can be changed in real–time by the inspector to enhance visualization. Positional information, elapsed scan time, and a color bar are displayed on the screen right.

Because the data must be visually compressed to fit in its 128x1024 pixel region, a strip chart graph plotting the maximum value for each revolution is superimposed on each channel display. All C–scan data are stored in RAM (and later to disk) so the compression is only for display purposes. The strip chart assists the operator in identifying possible flaws during the scan. Figure 4 shows a sample display with a 256 grayscale palette and actual billet C–scan data. Data are present on 5 of the 8 channels. The superimposed strip chart on each channel's data is clearly seen. In general, the scan shows a clean billet with only minor variations in signal due to material noise. However, channel 5 shows a possible indication towards the left side of the figure. Notice how the strip chart "spike" serves to draw attention to the signal.

SYSTEM OPERATION

For inspection, the billet is immersed in a water tank and rotated about its axis. The maximum billet rotation speed is approximately 30 RPM. The transducers, aligned normal to the billet surface, are mounted on a stage or "follower" that rides on a track over the tank. As the billet rotates the follower moves axially along the billet length and the material is inspected in a helical pattern.

An axial encoder is mounted on the follower and is used to report axial position of the transducers during the scan. A rotary encoder is coupled to an adapter which is attached to the end of the billet using double sided adhesive. This encoder generates a once–per–revolution index or home pulse which is used by the computer acquisition software to determine the 0° location on the billet. The rotary encoder also generates a 2048 pulse–per–revolution signal. This signal provides a position dependent trigger for the ultrasonic transducers known as a pulse–on–position or "POP" pulse. The POP signal is used by the electronics to synchronize the triggering of the transducers for all 8 channels to the billet rotation. Each channel will divide down the 2048 master POP to the sample rate required to inspect the particular zone.

As the zone radii increase, so does the circumference and therefore the number of samples required to inspect the material. For this reason, the outermost zones (beginning with channel 1) may sample the billet 1024 times per revolution, middle zones only 512 samples per revolution, inner zones 256, and so on to the center of the billet. The sample count is determined by taking the zone mean circumference, dividing it by half the beam diameter ε_x (Equation 2) and rounding that number up to the nearest power of 2. While transducers covering the larger radii zones fire more often than their smaller radii counterparts, all transducers fire simultaneously when they do trigger. This greatly

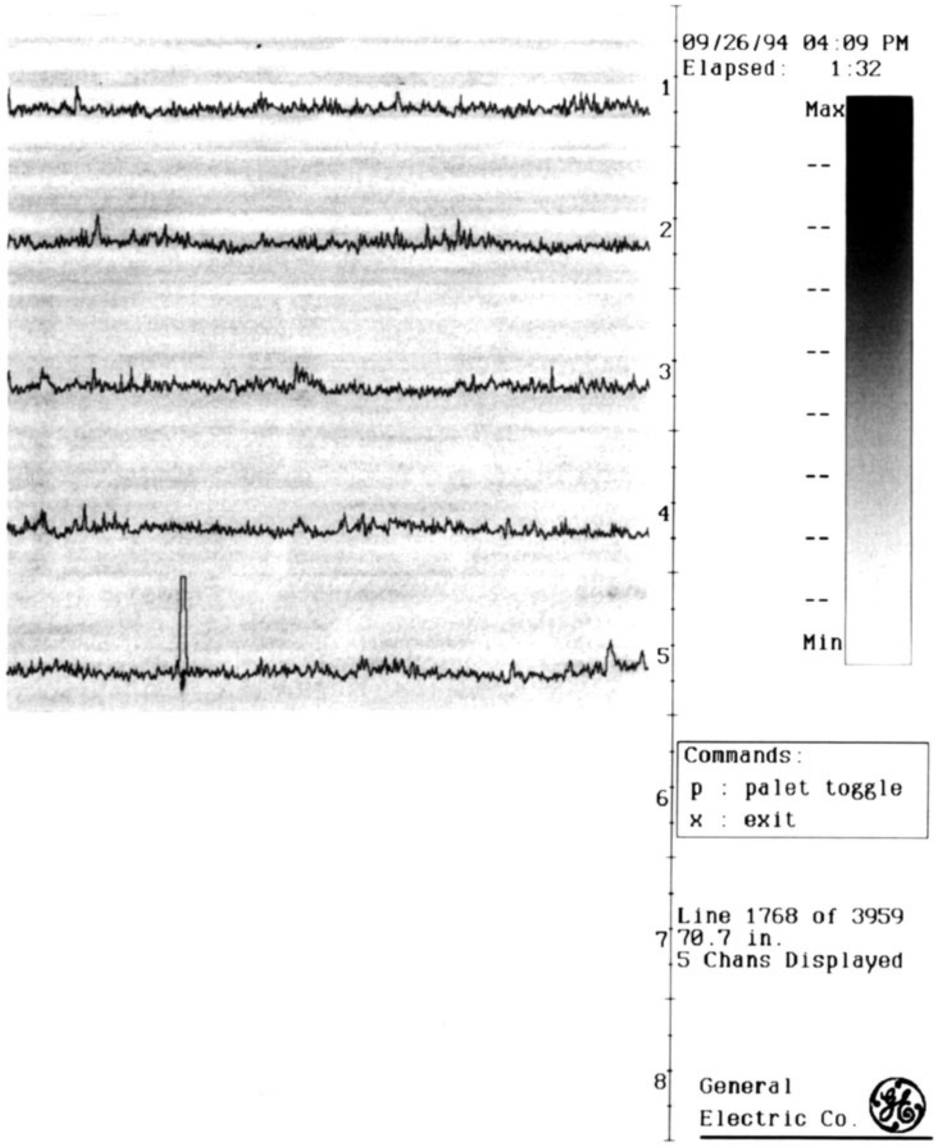

Figure 4. Multizone C–scan display

minimizes the possibility of any unattenuated sound from any channel interfering with the signal from any other channel.

Prior to inspection, the user must start the acquisition software on the computer. Based on the billet material and diameter, the operator is instructed on how to configure the electronics. Parameters such as attenuation, signal gate delay and width, and POP rate are set using thumbwheel switches on the electronics for the required number of channels. Information such as operator id, billet length, and identification numbers must be entered to the software as well.

Once the electronics are configured and the acquisition software is running, the rotary encoder begins triggering the electronics. The electronics fire the transducers and produce analog C–scan data values. These analog signals – along with a data ready end of

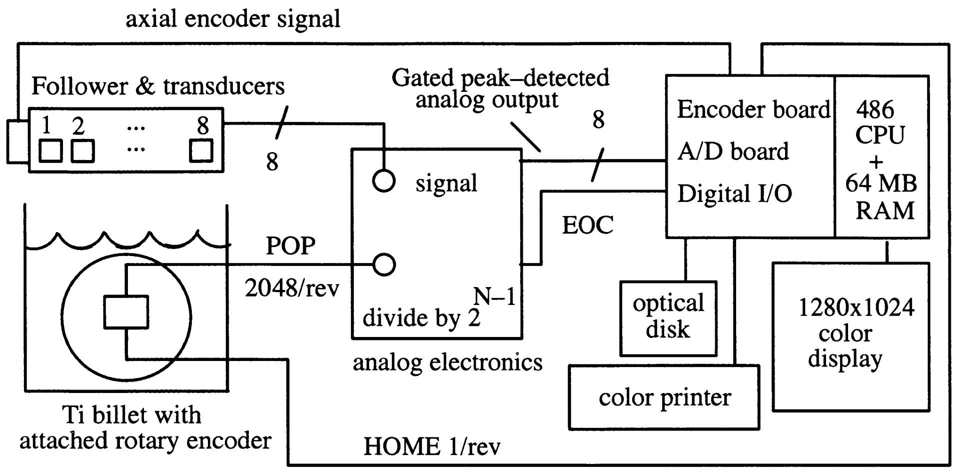

Figure 5. Multizone System Block Diagram

conversion (EOC) pulse – are sent to the PC acquisition software. An interrupt handler reads the C–scan values using an 8–channel simultaneous sample and hold (SS&H) A/D board. The C–scan data are stored in RAM and displayed for each revolution. The axial position of the follower is read for each revolution by the PC and recorded with the C–scan data.

Upon scan completion, the user is given the opportunity to enter any comments about the scan. Data is then transferred from computer memory to disk and later archived to WORM optical disk for permanent storage. The file format used is designed around a standard called Network Common Data Form (netCDF). [4] This public domain package was written by Unidata Program Center and is based on an interface developed by NASA called Common Data Format. It provides a self–contained, architecture independent, flexible means of transferring, storing, and accessing data of any type. Data can be transparently accessed on a variety of computer architectures and various commercial imaging packages provide capability to access files of this format. A complete block diagram of the Multizone system is presented in Figure 5.

POST SCAN ANALYSIS

The implementation of digital data acquisition allows post scan analysis which is not possible with any current billet inspection systems. A typical Multizone inspection on a single billet can generate 30 MB or more of ultrasonic image data. These data can include flaw signals obscured by an acoustic noise level that varies both circumferentially and axially along the billet. An image analysis software package was developed to aid the operators in finding indications. This package, which runs on the system PC, provides a Microsoft Windows based graphical user interface for displaying and manipulating the inspection results. Using these tools, the operator is able to locate signals which are above the local acoustic noise, display them at high resolution, and extract peak amplitude and signal to noise ratio (SNR) for each indication. Criterion based on both peak amplitude and SNR can be applied to the indication to make the accept/reject decision [2]. A 66 MHz, 486–PC can quickly review 30+ MB of data allowing the task to be completed before the billet is removed from the tank. Since the scan positional information is stored along with the image data, the operator can return the transducer to the location on the billet where an indication exists to verify its location and mark the billet for sectioning to remove the material surrounding the indication.

CONCLUSION

This paper describes a real–time, PC based, multiple channel system for ultrasonic inspection of billet material. Employing focused transducers and custom analog electronics, the system is reaching its goal of detecting hard–alpha and other materials defects as early in the manufacturing process as possible. Digital data storage allows for the use of image display and analysis of inspection results as well as providing a permanent record of the test. In addition to improving engine safety and reliability, the system can also be used to improve materials processing techniques for better titanium.

ACKNOWLEDGEMENTS

The authors would like to thank J. Moyers and the entire Inspection Staff at RMI Titanium Company for their technical inputs and for their cooperation and patience during system installation.

REFERENCES

1. R.J. Koenig, J.G. Costa, R.E. Gonzalez, R.E. Guyotte, D.P. Salvano, and T. Swift, "Titanium Rotating Components Review Team Report", US FAA Aircraft Certification Service Engine and Propeller Directorate, 14 December, 1990.
2. D.C. Copley, and P.J. Howard, "Operational Performance of a Multizone Billet Inspection System", Review of Progress in QNDE, these proceedings.
3. H.T. O'Niel, Journ. of Acoust. Soc. Am., vol. 21, p. 516, 1949.
4. R. Rew, G. Davis, and S. Emmerson, "NetCDF User's Guide", Unidata Program Center, April 1993.